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ROTATION OF THE ION COMPONENT OF A HOT CATHODE PENNING DISCHARGE PLASMA

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In a cylindrical column of an inhomogeneous plasma, located in /2004* a uniform axial magnetic field, macroscopic azimuthal charged particle fluxes may appear. The azimuthal motion of the plasma components may be the result of effects which are similar in form but different in nature, namely: drift of the charged particles in the crossed electrical and magnetic fields and Larmarovskiy drift", connected with the radial pressure gradient of the plasma components. In real plasmas both of the above-mentioned effects, in principle, contribute to the azimuthal particle motion [1,2]. The rotation of the components of an inhomogeneous plasma, located in a magnetic field, is an important characteristic of the latter and, in particular, one of the factors determining the stability of the plasma system [3]. A number of low frequency plasma instabilities are directly connected with the presence of azimuthal charged particle fluxes in the plasma [2,4-7]. Therefore, an investigation of the characteristics of the macroscopic rotation of the plasma components and its physical nature in a number of cases may contribute to the establishment of a type of instability [2] and, consequently, is of undoubted interest.

The purpose of the present study was to investigate the rotation of the ion component of a plasma in a Penning discharge with a hot cathode, widely used in ion sources. It is known that a plasma of this discharge is characterized by radial gradients of potential, density and electron temperature [8] and also by the presence of low frequency oscillations [9-14], the nature of which has not as yet been unambiguously established, in a wide range of

*Numbers in righthand margin indicate pagination in the foreign text.

parameters of the discharge.

The experiments were conducted on the device described in detail earlier [13], with a discharge chamber of the following dimensions: diameter of the anode—54 mm, diameter of the cathode—12 mm, length of anode—110 mm, cathode-reflecter distance—130 mm. A stationary discharge in helium with a current intensity $I_a = 1$ A and a discharge voltage $V_a = 100$ V was reported in the system. The investigations were conducted at five fixed helium pressures in the discharge chamber ($8.4 \cdot 10^{-3}$; $1.1 \cdot 10^{-2}$; $1.3 \cdot 10^{-2}$; $1.6 \cdot 10^{-2}$; $2.0 \cdot 10^{-2}$ mm of mercury) in the range of variation of the axial uniform magnetic field intensity from 100 to 600 e. The above-mentioned ranges of variation of helium pressure and magnetic field intensity include both the region of stability of the discharge plasma and the region of the appearance in it of low frequency oscillations with an azimuthal mode m = 1, 2, 3 [13].

As follows from the formulation of the problem and the experimental conditions, the method of measuring the macroscopic velocity of the azimuthal motion of the ion component of the plasma must possess (1) a sufficiently high sensitivity, because the expected value of the direct azimuthal velocity of the ions is on the order of their thermal velocity, (2) sufficiently high spatial resolution in connection with the small volume of plasma studied, and (3) the minimal disturbing influence of the plasma.

Among the previously described methods of determining the velocity of an azimuthal ion flux in a gas discharge plasma [1, 2, 15], the above-mentioned requirements are most fully satisfied by the method of a plain, unidirectional-oriented probe [2], analogous to the method of separating the directional part of the distribution function of electrons according to velocities, examined by Granovskiy [16]. According to this method, the velocity of the /2005 ordered motion of ions may be determined according to the formula

$$v_\theta = \frac{I_1 - I_2}{I_2} v_т .$$

where I_1 and I_2 are the ion saturation currents on a probe, oriented correspondingly counter to and in the direction of the ion azimuthal motion;

$v_т = \sqrt{\frac{3}{2}\frac{kT_e}{M}}$ [17], T_e — the electron temperature; M — the ion mass.

The probe used in the present experiment was a molybdenum disc with a diameter of 2 and a thickness of 0.2 mm, one of the flat surfaces of which was covered with a thin alundum film and protected from being covered with dust by an additional metallic screen. The probe was able to move along the radius of the anode and to rotate relative to the axis, lying in the plane of the probe and congruent with its radius.

The electron temperature which must be known in order to determine v_T was measured by means of a single cylindrical langmuir probe; the latter can be moved along the radius of the system. The small diameter of the probe (0.1 mm) and its orientation perpendicular to the magnetic field justify the use of this method in range of magnetic fields studied [18]. The true coordinate recorder P. D. S. 021 was used for recording the probe characteristics. All measurements were made in the middle plane of the anode in the plasma beyond the limits of the flux of primary electrons.

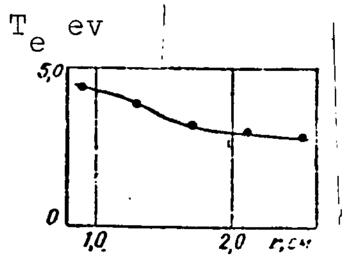


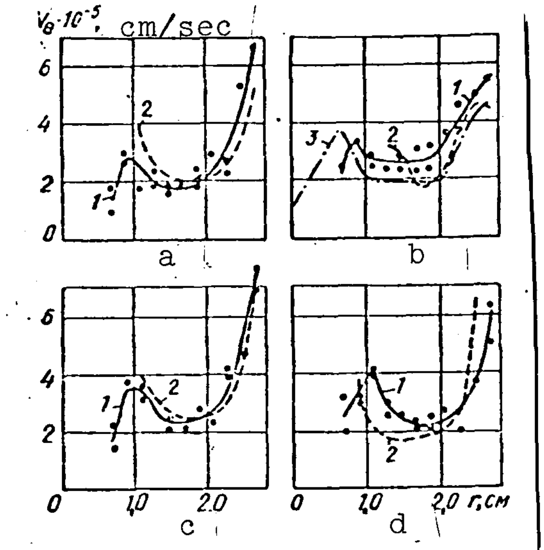
Figure 1. Radial Profile of the Electron Temperature ($p = 1.3 \cdot 10^{-2}$ mm mercury, H = 120 e).

The electron temperature, determined at different distances from the axis of the system, at different helium pressures and magnetic field intensities, was usually measured in the range of 3 to 7 ev. A typical radial profile of the electron temperature for these conditions is shown in Figure 1. An increase in the electron temperature upon approaching the axis of the discharge is characteristic; this increase is very weakly expressed in the prianode region of the plasma and becomes more noticeable upon approaching the flux of primary electrons. The radial temperature drop in the plasma region investigated usually did not exceed 1.5 ev with the exception of conditions with intense disturbance of the plasma by low frequency oscillation with a mode m = 1, in which a significant overall increase in temperature was observed (to 15—20 ev), and its radial drop reached 7 ev.

The variations in electron temperature pressure and magnetic field intensity corresponded to those described earlier [13].

The measurements made showed that in the above-mentioned range of discharge conditions there exists ion azimuthal motion in the direction of the plasma drift in cross electrical and magnetic fields in the presence of radial "sagging" of the potentials. Reversal of the direction of the magnetic field led to an analogous change in the direction of the ion azimuthal velocity. In all cases, the rotational velocity of the ion component of the plasma /2006

v_o varied within the limits (from 1.5 to 8) · 10^5 cm/sec and in order of magnitude and direction coincided with the phase velocity of the observed azimuthal waves.



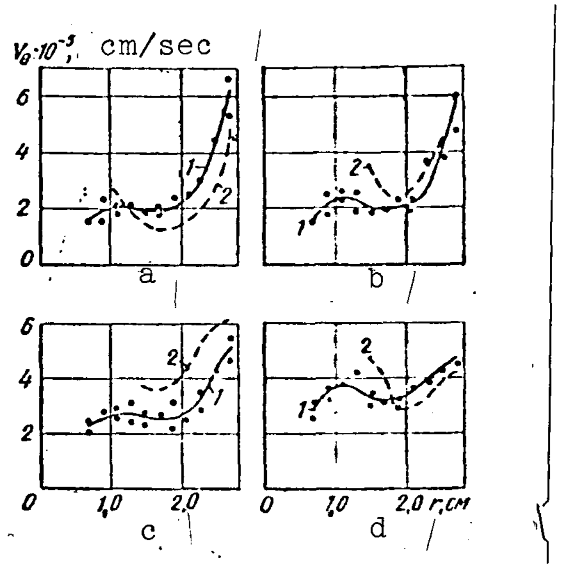


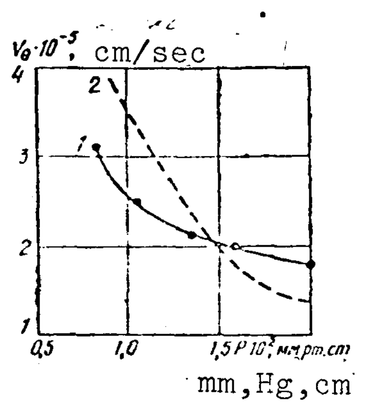
Figure 2. Radial Profile of the velocity of the ion azimuthal motion ($p = 1.6 \times 10^{-2}$ mm mercury); 1—experiment, 2 and 3—calculation: a—H = 135 e, oscillations absent; b—H = 210 e, oscillations with m = 2 and f = 41 kHz; c—H = 240 e, oscillations with m = 3 and f = 74 kHz; d—H = 435 e, oscillations with m = 1 and f = 31 kHz.

Figure 3. Radial Profile of the velocity of the ion azimuthal motion (H = 190 e, oscillations with m = 2, 1—experiment, 2—calculation): a—$p = 2.10^{-2}$ mm mercury, f = 38 kHz; b—$p = 1.3 \cdot 10^{-2}$ mm mercury, f = 45 kHz; c—$p = 1.1 \cdot 10^{-2}$ mm mercury, f = 48 kHz; d—$p = 8.4 \times 10^{-3}$ mm mercury; f = 56 kHz.

Seven to ten radial velocity profiles of the ion azimuthal motion, corresponding to different magnetic field intensities in the range of 100 - 600 e, were measured for each fixed helium pressure. The radial profiles were determined at a spacing of 2 mm and one to two measurements of v_θ made in each probe position. As an example, reflecting the general properties of the obtained radial dependences of v_θ, Figure 2 shows several radial profiles of v_θ for an invariable pressure of $p = 1.6 \cdot 10^{-2}$ mm mercury and different magnetic field intensities, and Figure 3—for an invariable magnetic field H = 190 e and different pressure. The most important characteristic of these dependences is the significant radial non-uniformity of the rotational velocity of the ion: a weak change in the velocity v_θ in the plasma layer adjacent to the flux of primary electrons is replaced by a rapid increase in the prianode layer. Against the background of the weak variation in the rotational velocity of the ion in the region adjacent to the flux of primary electrons it is possible to observe an outlying drop in the value of v_θ to the axis of the system and a shallow minimum at the distances r = 1.3 to 1.7 cm. The absence of linear dependence of the rotation speed on the radius testifies to the fact that representation of the rotation of the ion component of the plasma as of the rotation of a solid body with a single angular velocity is not applicable in the present case.

Investigations showed that in the plasma region adjacent to the flux of primary electrons, the rotational velocity of the ion component increases with a decrease in the gas pressure in the discharge chamber. The dependence shown in Figure 4 may serve as an illustration of this. /2007

With a change in the magnetic field the azimuthal rotation velocity of the ions in this region changes insignificantly (changes in the order of the spread of experimental data, which reached 20%) up to a magnetic field intensity of approximately 500 e, above which it begins to increase markedly. The corresponding dependence is shown in Figure 5.



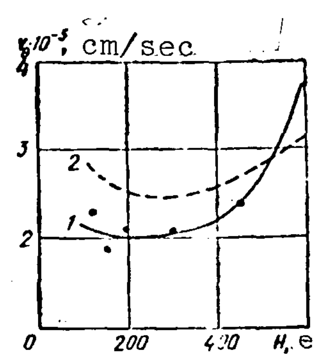


Figure 4. Dependence of the velocity of the ion azimuthal motion on the gas pressure (H = 190 e, r = 1.7 cm): 1—experiment, 2—calculation.

Figure 5. Dependence of the velocity of the ion azimuthal motion on the magnetic field intensity (p = 1.3 · 10^{-2} mm mercury, r = 1.7 cm): 1—experiment, 2—calculation.

In hydrodynamic approximation, a theoretical calculation of the rotational velocity of the ions in a cylindrical plasma column, located in a uniform magnetic field, with a radial electric field present in it, the concentration gradient and the ion collisions with neutral patterns was made in [1]. Assuming a weak change in the azimuthal velocity component along the radius and axial symmetry of the stationary plasma parameters from the vector equation of motion of the ions

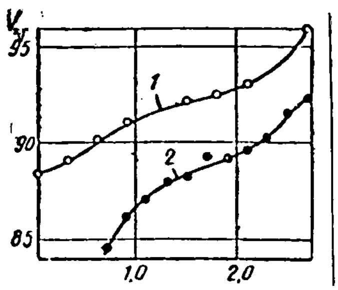
$$M\frac{d\vec{v}}{dt} = c\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{H}\right) - \frac{\vec{\nabla} P_i}{n} - \frac{M\vec{v}}{\tau} \qquad (1)$$

there was obtained a cubic equation for determining the angular rotation frequency of the ion component of the plasma:

$$\left(\frac{\omega}{\Omega}\right)^3 + 2\left(\frac{\omega}{\Omega}\right)^2 + \left\{1 + \frac{1}{(\Omega\tau)^2} + \frac{1}{r\Omega^2}\left(\frac{eE_r}{M} - \frac{1}{Mn}\frac{\partial P_i}{\partial r}\right)\right\}\left(\frac{\omega}{\Omega}\right) + \frac{1}{r\Omega^2}\left(\frac{eE_r}{M} - \frac{1}{Mn}\frac{\partial P_i}{\partial r}\right) = 0, \qquad (2)$$

where $\frac{\partial P_i}{\partial r} = T_i \frac{dn}{dr}$ is the pressure gradient of the ion component of the plasma; E_r is the radial electric field; e is the ion charge; M is the ion mass; T_i is the ion temperature in electron volts; n is the plasma concentration; τ is the mean time between ion collisions with neutral atoms; Ω is the ion cyclotron frequency; $\omega = \frac{v_\theta}{r}$ is the angular rotation frequency of the ion at the distance r from the system axis. /2008

It was of interest to calculate v_θ to equation (2) and to compare this with the experimentally measured values. Data on $E_r, \frac{1}{n}\frac{dn}{dr}$, T_i and τ, were necessary for this. The field E_r was determined according to the radial potential profiles of the floating probe, which, strictly speaking, is justified only under the assumption of a constant electron temperature in the plasma volume. As follows from the results of measuring the electron temperature (see Figure 1), this assumption is completely justified in our experiments. Only in the plasma region directly adjacent to the primary electron flux, was it possible to expect a deviation of the fields measured with the aid of the floating probe from the two fields on the side of an overestimation.

a) 

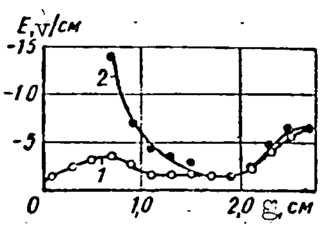
b) 

Figure 6. a—radial profiles of the plasma potential (1) and the potential of the floating probe (2);
b—corresponding radial profiles of the electric field.

A comparison of the electric fields, determined according to the radial profiles of the floating probe potential and the true plasma potential was performed for one of the discharge conditions for direct verification of these considerations. Measurement of the true plasma potential was performed by means of an emitting floating probe [19], the use of which in the entire range of discharge conditions studied proved to be inexpedient in view of the significant technical difficulties. Corresponding data, shown in Figure 6, indicate the fact that in the plasma region from $r = 1.5$ cm to the anode wall there is good agreement of the values of the fields, determined by both methods mentioned, is observed. This agreement is gradually destroyed upon approaching the primary electron flux. The difference becomes significant in the immediate vicinity of the primary electron flux, where the floating probe potential is greatly lowered due to the presence of high speed electrons in the plasma.

A characteristic feature of the radial profiles of E_r, determined in the entire range of variation of discharge conditions, is the fact that at distances r = from 1.3 to 1.7 cm from the system axis, the field reaches a minimum value (see Figure 6, b) in the region of this minimum $E_r = -(1—3)$ v/cm; in the prianode plasma region the fields reached $-(5—6)$ v/cm.

The value $\frac{1}{n}\frac{dn}{dr}$ was determined according to the radial profiles of the plasma density in a discharge, measured by the probe method, and amounted to from -1 to -3 cm^{-1}. The ion temperature in the present experiment was not measured, however, as follows from the literary data, in similar discharges, it is low and in any case does not exceed $0.1\ T_e$ [5, 10]. Thus, in our conditions the term $\frac{eE_r}{M}$ in equation (2) significantly exceeded the term $\frac{1}{Mn} \frac{\partial P_1}{\partial r}$ and in first approximation, the latter may be ignored, which was done below. The direction of rotation of the ion component of the plasma, established experimentally, in particular, also indicates the validity of such an approximation. For a rough estimate of the value of τ it is possible to use the formula /2009

$\frac{1}{\tau} = \nu_o = 3.2 \cdot 10^7 \cdot p$ (mm mercury) [20], the use of which is justified in the case of a low ion temperature. In this case the radial profiles of the ion azimuthal motion velocity, calculated according to equation (2) and measured experimentally, qualitatively agree well with one another, however, the calculated values of v_θ exceed the experimental one by two to three times. It is shown below that a significantly better quantitative agreement is achieved with the use of the formula for determining τ

$$\frac{1}{\tau} = \nu_0 + A\left(\frac{Ep}{M}\right)^{1/2},$$

$$E$$

derived in [21] for the case of $\frac{E}{p}$, which was realized in the present experiment. The constant A (the single unknown in the last formula) was determined according to the value of τ, obtained by means of substituting the experimental values of ω and E_r into equation (2). Such an operation was performed for four pairs of values of ω and E_r, for arbitrarily selected discharge conditions in a region of weak variation of v_θ with the radius, where the assumptions made in deriving equation (2), are well founded. As might be expected, the values of A calculated in such a way proved to be close to one another and for further calculation, the value $A = 5.3 \cdot 10^6$ was used, if E is expressed in volts per centimeter, M—in atomic units and p in millimeters of mercury.

Calculation of ω was performed in the entire range of variation of p and H investigated, which made it possible to compare the theoretical profile corresponding to each experimentally obtained radial profile of v_θ. Examples of such a comparison are given in Figures 2 and 3. It is obvious that in the greater part of the cross section of the plasma column the results of calculation and experiment agree well not only qualitatively but also quantatively. Comparison of experimental and theoretical values of v_θ in the plasma, directly adjacent to the primary electron flux, prove to be impossible, since in this region the values of E_r, necessary for calculation, were determined by the floating probe method with a great degree of error (see Figure 6). Good agreement of experiment and theory for the entire radial profile of v_θ , including the indicated region, is obtained with the use of values of E_r, determined according to the radial profile of the true plasma potential (see Figure 2, b, curve 3). The dependences shown in Figures 4 and 5 also indicate satisfactory agreement of theory and experiment. Results of a comparison make it possible to uniquely connect the radial non-uniformity of the rotation velocity of the ion with the radial non-uniformity E_r in the discharge, and the observed increase of v_θ with a lowering of pressure—with the decrease in ion collisions with neutral atoms.

The result presented above may be summarized in the following way.

1. It is experimentally established that in a hot cathode Penning discharge in the range of discharge conditions examined, ion azimuthal fluxes take place. It is shown that the cause of the azimuthal motion of the ion component of the plasma is, chiefly, the ion drift in the crossed radial electric and axial magnetic fields in the presence of collisions with neutral atoms. /2010

2. Radial profiles of the linear velocity of the ion azimuthal motion, indicating an absence of radial uniformity of the angular velocity of this motion, are obtained.

3. It is shown that equation (2), derived in [1], well describes the azimuthal motion of the ion component of the plasma in the condition investigated.

4. It is experimentally established that the phase velocity of the low frequency oscillations arising in the discharge plasma coincide in direction and order of magnitude with the azimuthal motion velocity of the ion component of the plasma.

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16. Abstract

The roattion of the ion component of the hot cathode Penning discharge plasma was investigated. The dara on radial profiles of linear velocity of the ion azimuthal motion are obtained. These data evidence for the absence of radio uniformity in angular velocity of this motion. The calculation of the radial profiles of the ion azimuthal motion velocity is carried out, using the equation obtained in [1]. The results of the experiment are in good agreement with the calculation. The rotation of an ion component of plasma is shown to be chiefly due to drift of ions in crossed radial electric and axial magnetic fields with the presence of ion collisions with neutral particles.

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